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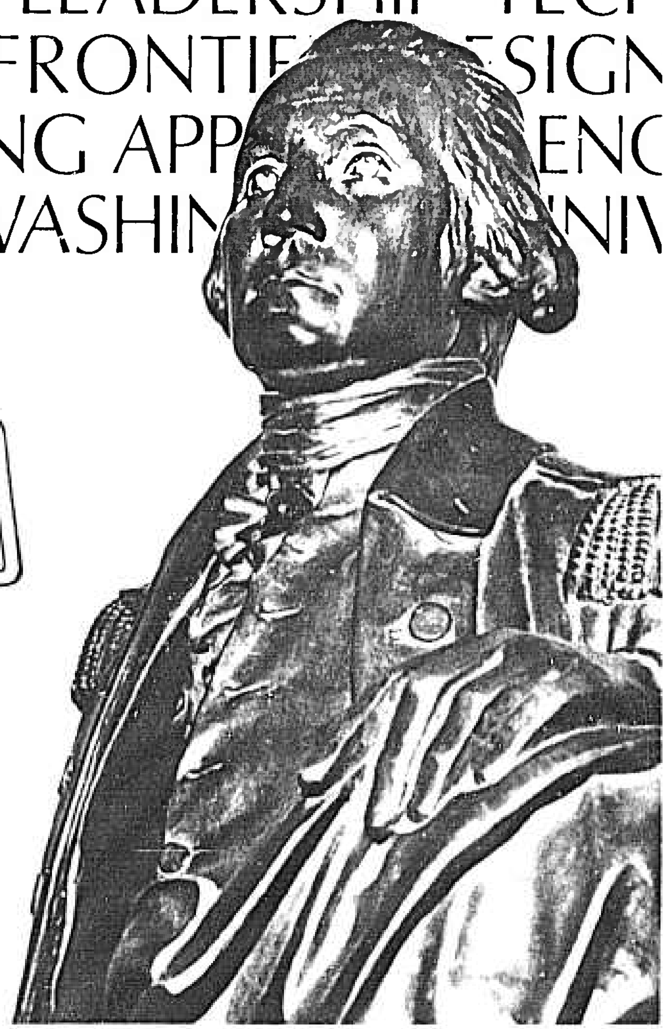

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ROOM TEMPERATURE CREEP OF Ti-6Al-4V

by

M. A. Imam and C. M. Gilmore

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SCHOOL OF ENGINEERING AND APPLIED SCIENCE
The George Washington University
Washington, D. C. 20006

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ABSTRACT

Recent investigations have shown that Ti-6Aℓ-4V can exhibit an appreciable amount of creep at room temperature. In the present investigation three different microstructures (α-β anneal, recrystallization anneal and β anneal) of Ti-6Aℓ-4V were examined under dead weight torsional step loading. The loading sequence was forward, reverse and 2nd forward loading. It was concluded that even at a stress level well below the yield point the alloy exhibits creep in forward loading and increasing creep strain in reverse loading and 2nd forward loading. In addition the threshold stress for creep initiation is much lower in reverse loading and 2nd forward loading in comparison to forward loading. Furthermore the rate of creep at constant stress was different in different microstructures of the alloy; the maximum creep rate occurred with the recrystallization anneal and the minimum creep rate occurred with the β anneal. This type of creep would be important in design of structures subjected to long time cyclic loading.

LIST OF FIGURES

INTRODUCTION

Observation of room temperature creep in titanium alloys such as Ti-6Aℓ-4V has been reported by several authors[1-7]; however, considerable controversy still exists concerning the presence of room temperature creep. For example Wood[2,3] reported that room temperature creep occurred in Ti-6Aℓ-4V at stresses as low as 10 percent of yield. However, Riemann[6] recently reported that room temperature creep below yield did not occur at all if the loading was unidirectional, but room temperature creep did occur if the stress was reversed after exceeding the yield stress in the forward direction. Later work by Odegard and Thompson[7] disputed Riemann's results with their observation of room temperature creep at tensile stresses of about 60 percent of the yield stress. Odegard and Thompson also made the interesting observation that the creep was independent of microstructures.

EXPERIMENT

To clarify some of these divergent results we decided to perform additional tests of low temperature creep in Ti-6Aℓ-4V. The specimens for these tests were thin walled-seamless tubes of .25 in O.D. and .212 I.D. The chemical composition of the Ti-6Aℓ-4V alloy is in weight percent:

Al	V	O	N	C	N	Fe
5.8	4.4	.113	69ppm	.02	.010	.08

In this work we wanted to see if the creep rate and the total amount of creep was dependent upon microstructure; fortunately the work of Odegard and Thompson[7] was not yet published when we initiated this work. We chose to investigate three microstructures resulting from different annealing treatments: α-β anneal (αβA), recrystallization anneal (RA), and β anneal (βA). The procedures for these annealing treatments are as follows:

α-β Anneal (αβA) or Fully Annealed

800°C (1472°F) for 3 hours, furnace cool (FC) to 600°C (1112°F), followed by air cool (AC) to room temperature.

Recrystallization Anneal (RA)

928°C (1702°F) for 4 hours, FC to 760°C (1400°F) at 180°C/hour, FC to 482°C (900°F) at 372°C (702°F)/hour, AC

β Anneal (βA)

0.5 hour at 1037°C (1900°F), AC to room temperature, 732°C (1350°F) for 2 hours, AC to room temperature.

The microstructures produced by these three annealing treatments are shown in figures 1, 2 and 3.

The mode of loading for this test will be by dead weight in shear. This is the same mode as used by both Wood[2,3] and Riemann[6]; however, Odegard and Thompson's[7] work was with tensile loading. One major difference between the work of Wood and Riemann is that in Wood's work the strain was measured by reflection of a light beam from a mirror on the driving grip that attached to one end of the specimen; Riemann attached his mirrors to the specimen. Attaching the mirrors to the specimen eliminates the possibility of recording any grip slippage as specimen strain. Since it has been suggested that Wood's observation of creep at stresses well below yield could be due to slippage in the grips, we have designed a strain measuring system that is schematically shown in Figure 4. A static load is applied to a pulley that converts the load into a torque about the specimen axis. The strain is measured with two mirrors that are attached to flats on brass collars that slide over the specimen. The collars are each attached to the specimen with three conical set screws spaced at 120° around the specimen. Only the set screws touch the specimen, and thus the spacing between the set screws of the two mirros determines the gage length. The collars are machined so that the gage length is always one inch. The twist strain is measured by determining the relative change in tilt of the two mirrors. By taking the relative tilt of the two mirrors any slippage in the grips is eliminated from the measurement. The relative tilt angles are determined by using a laser source of light and collimating it to get a line. The single line is split by the two mirrors and each beam is reflected to a circular scale one meter from the specimen. The laser source provides a sharp bright image in comparison with the incandescent sources we have tried. We estimate that we can measure shear strain as low as $2x10^{-5}$ with this device. In these tests our procedure was to measure the strain until no strain could be detected in a 24 hours period. Then the load was increased by an increment. The loading was continued until the specimen yielded, the total strain at yield was also recorded. The specimen was then unloaded and loaded in the reverse direction following the same procedure. The loading was reversed again so that the final loading was in the same direction as the initial loading; we will call this forward, reverse and 2nd forward loading.

RESULTS AND DISCUSSION

The results of the forward, reverse and 2nd forward loading are shown for the 3 heat treatments in figures 5, 6, and 7. The steps in the stress vs strain curve indicate the total accumulated creep strain at that stress. The accumulation of strain with time at each stress is presented in detail in Appendix A. The data in figures 5 through 7 show that there is transient creep at stresses well below yield; however, the creep upon initial forward loading is much smaller than that for reverse loading. For example from Appendix A a transient creep strain of 0.13×10^{-3} is observed for the recrystallization annealed treatment with forward loading at a stress of 23,737 psi. For reverse loading a transient creep strain of 1.57×10^{-3} is observed at reversed stress of 23,737 psi. Thus transient creep is observed for stresses well below the yield; however, exceeding the yield in the forward direction and reversing the stress results in an increase of transient creep by nearly an order of magnitude and the creep starts at a significantly lower stress. Initial loading was always done in increments of 4747 psi (2 lbs weight) until transient creep was observed, then the load was increased in increments of

11868 psi (5 lbs weight). Thus the point of initial transient creep is only known to within ± 4747 psi. The observation of increased creep strain after stress reversal is of course the well known Bauschinger effect. The large strain in the reverse direction does not occur without the large plastic strain in the forward direction.

The data of figures 5 through 7 also show that there is a definite dependence of the creep strain upon microstructure. For example (see Appendix A) in reverse loading at a shear stress of 47,474 psi the total creep strain in the RA material was 4.15×10^{-3}, in βA material it was 1.178×10^{-3} and in αβA material it was 2.99×10^{-3}. This ordering to creep results was consistently observed; the creep was greatest in the RA material followed by αβA material and the βA material generally demonstrated the least creep. This ordering of results is shown clearly in Figures 8, 9, and 10 which show the creep strain in the three treatments as a function of time for forward, reverse, and second forward loading at a stress of 71,211 psi. Observe that the creep strain in the fully (αβ) annealed and recrystallization annealed alloys approach each other after one full cycle, but the β annealed alloy continues to have less creep strain.

These experimental creep results can be related to the microstructure. The RA material shown in Figure 2 has large α grains relative to the other microstructures and thus dislocations can move considerable distances before encountering grain boundary barriers. The βA material shown in Figure 3 has a fine grain size, thus dislocations cannot move very far before a grain boundary is encountered and thus creep strain is less. Odegard and Thompson[7] have observed that creep in Ti-6Aℓ-4V is independent of microstructure. It is possible that the activation energy for creep is independent of microstructure, but the observation that the total creep is dependent upon microstructure indicates that it cannot be said that the creep is independent of microstructure. Further evidence of the dependence of creep upon microstructure is given in Figure 9 where the creep rate for the three microstructures is shown as a function of time at a stress of 71,211 psi. Since both accumulated creep and creep rate are functions of microstructure there is no question that the creep is a function of microstructure even though the activation energies may be equal.

In general the RA material has demonstrated the largest creep strain and the βA material the smallest creep strain. The one deviation to this order is demonstrated in Table 1 that shows the stress where transient creep was first observed for each direction of loading. The RA material consistently had the highest stress for creep initiation and the βA material consistently had the lowest stress where creep was observed. We should note that the stress increment used in this test was 4747 psi, so it is likely that the real differences in the stress where creep initiates is smaller than that observed in Table 1. However, there does appear to be a trend that indicates a decrease in the stress necessary to initiate creep deformation in the order RA, αβA and βA. This order may be due to the different temperature where the α-β microstructure is equilibrated. The α and β phases are equilibrated in the RA material at 928°C, in the αβA material the phases are equilibrated at 800°C and in the βA material the α and β phases are equilibrated at 732°C. With these equilibration temperatures the RA material would have the greatest concentration of aluminum solid solution atoms in the α phase and the βA material would have the smallest concentration of aluminum solid solution atoms in the α phases as is shown by Fopiana etal[8]. The RA material with the largest aluminum solid solution composition should have its dislocations more securely pinned than the other treatments thus a larger stress is necessary to unpin the dislocation. However, once the dislocations become unpinned in the RA material they can move large distances before they encounter a major obstacle such as a grain or phase boundary.

Another important observation from Table 1 is the continuous decrease in the stress where creep is observed as the stress is cycled from forward to reverse and second forward loading. Since yielding occurs in these alloys at 71211psi, true elastic behaviour is observed to only about 26% of yield (18980 psi) in forward loading,but cyclic loading has reduced the true elastic behaviour to only 6.6% (4747 psi) of yield after one cycle. A continuation of this trend could result in the elimination of any truly elastic behaviour because of the Bauschinger effect.

CONCLUSIONS

1. Transient creep is observed at stresses as low as 6.6% of the yield stress, this low stress creep occurred after a full cycle of loading that exceeded the yield point.

2. Transient creep was observed at stresses as low as 20% (β anneal) of yield during initial forward loading. Reversal of loading after yielding caused a significant increase in the creep strain, and a reduction of the elastic limit.
3. The creep strain was observed to be a function of microstructure, at high stresses RA material demonstrating the largest creep strains and the βA material the smallest creep strains.
4. The stress at which creep was initiated (elastic limit) was observed to be a function of microstructure and composition. The RA material had the largest elastic limit and the βA annealed material had the lowest elastic limit. These results in 3 and 4 indicate that the mechanism for elastic bahaviour and for strain hardening have a very different material dependence.
5. In the recrystallization annealed material, strain hardening was not able to stop the plastic deformation at the maximum stress of 71,211 psi; the test had to be terminated because of the lack of strain hardening.

TABLE I

Stress where transient creep was first observed for each direction of loading:

Anneal Treatment	Forward Loading	Reverse Loading	2nd Forward Loading
RA	18990 psi	9495 psi	9405 psi
αβA	18990 psi	9495 psi	4747 psi
βA	14242 psi	9495 psi	4747 psi

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7. B. C. Odegard and A. W. Thompson: Met. Trans., 1974, Vol. 5, pp. 1207.

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Figure 1. Optical micrograph of α-β annealed alloy.

Figure 2. Optical micrograph of recrystallization annealed alloy.

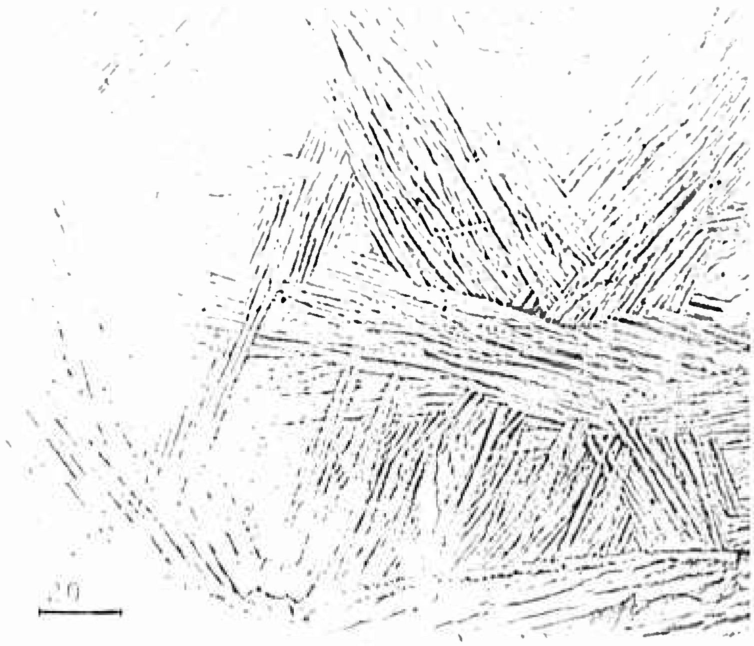


Figure 3. Optical micrograph of β annnealed alloy.

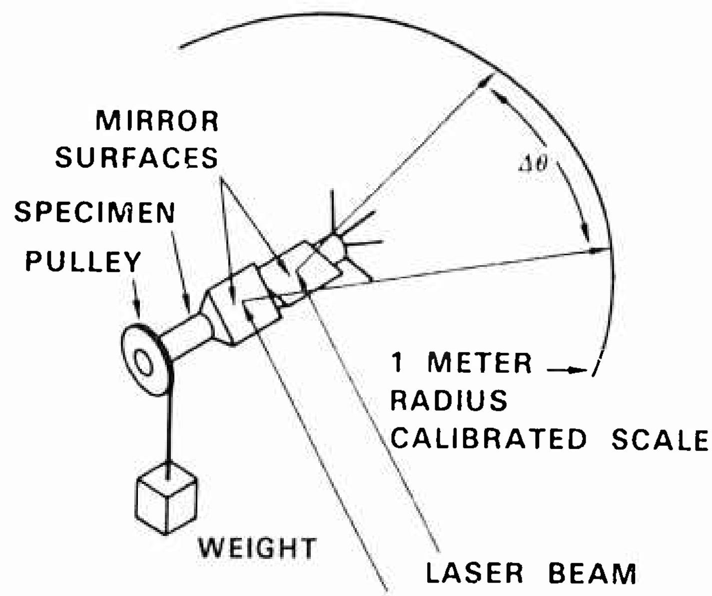
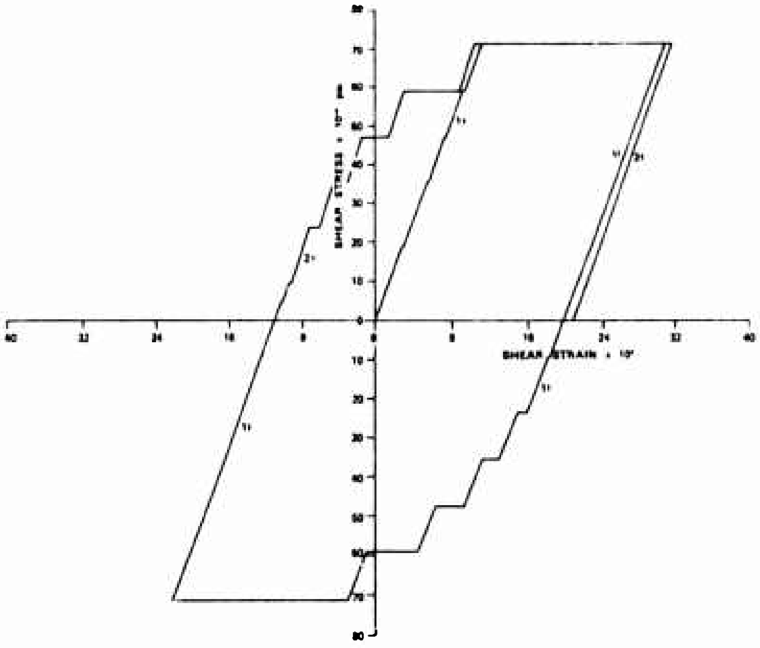
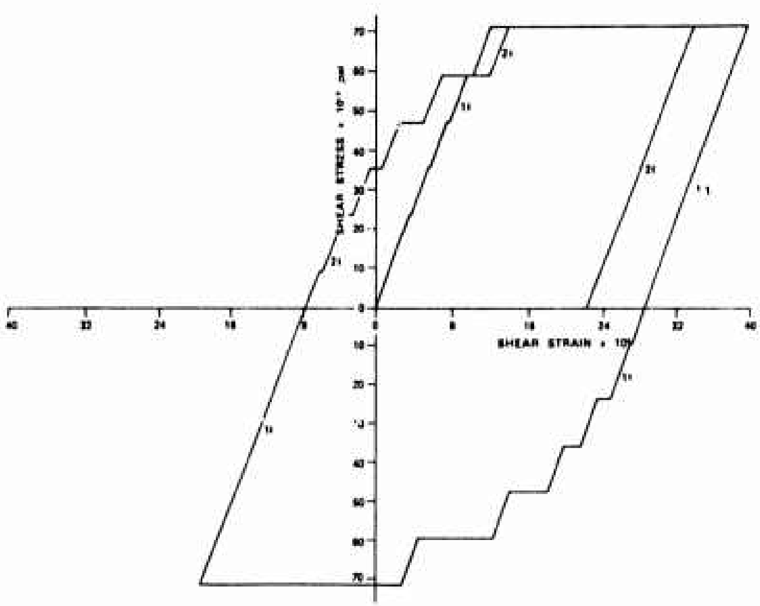


Figure 4. Schematic of the static torsion creep facility. The shear stress is applied to the tubular specimen by a weight attached to a pulley. The specimen is clamped in a pair of grips; the front grip is rotatable, and the rear grip is fixed. Two mirrors are attached to the specimen by three conical set screws at 120° separation for each mirror; the distance between the attachment screws is the 1 inch gage length. The relative tilt between the two mirrors is measured with a single laser beam that is split by the two mirrors and reflected to a 1 meter radius calibrated scale.



FULLY ANNEALED

Figure 5. Stress vs strain for fully annealed alloy with incremental loading in the forward, reverse and second forward direction. The horizontal segments indicate the total accumulated strain at a fixed stress.



RECRYSTALLIZATION ANNEALED

Figure 6. Stress vs strain for recrystallization annealed alloy as in Figure 5.

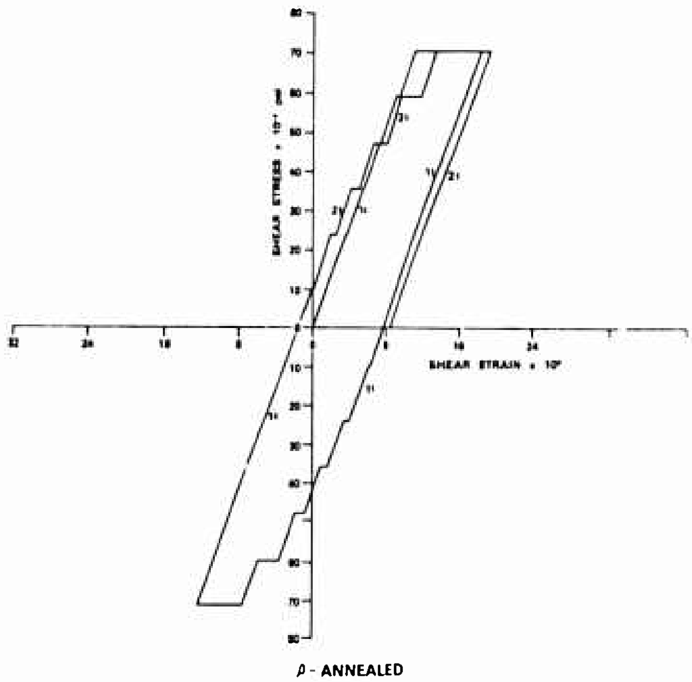


Figure 7. Stress vs strain for β annealed alloy as in Figure 5.

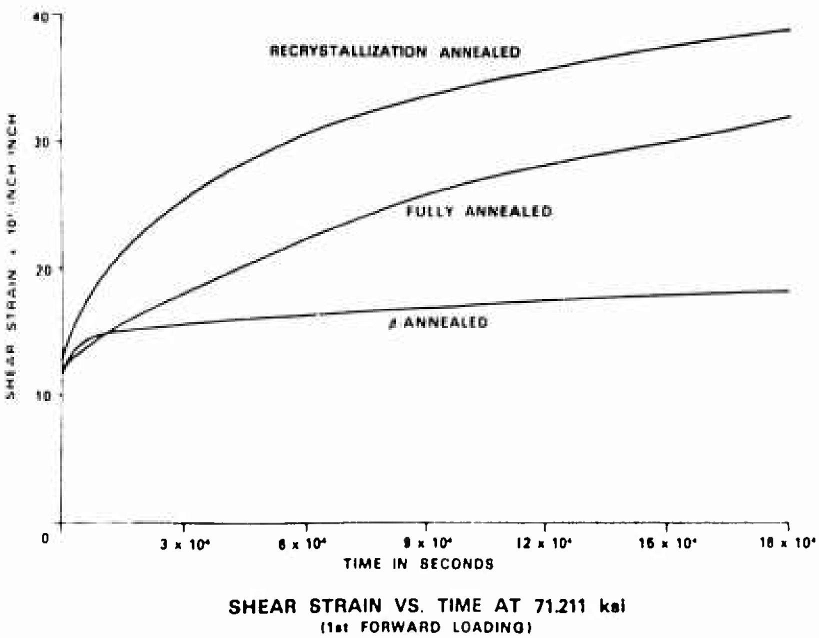


Figure 8. Strain vs time for forward loading.

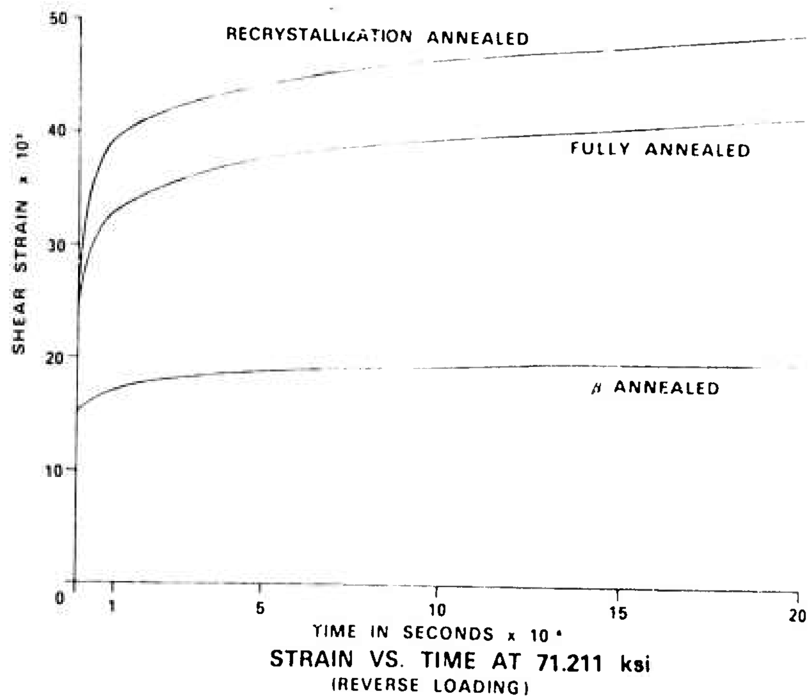


Figure 9. Strain vs time for reverse loading.

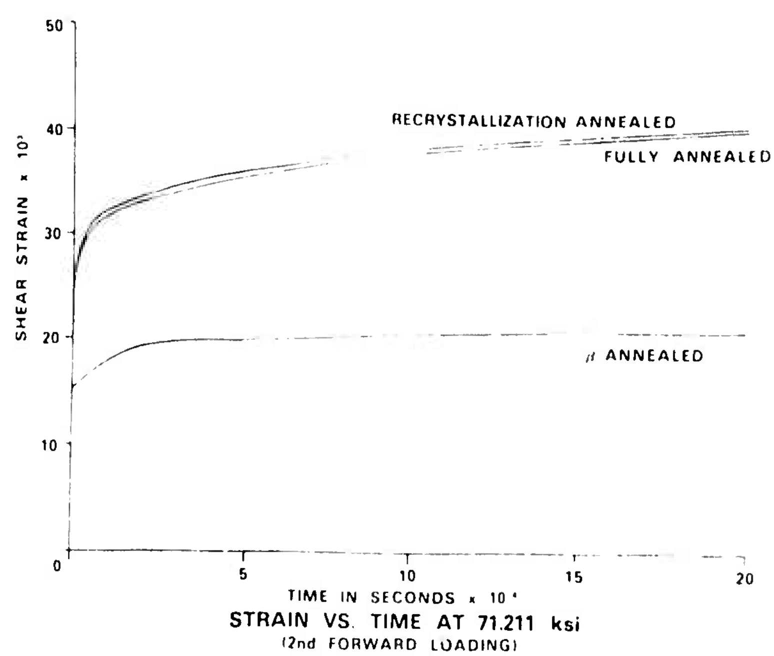


Figure 10. Strain vs time for second forward loading.

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APPENDIX A

SHEAR STRAIN AS A FUNCTION OF STRESS AND TIME

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A.1 β ANNEALED ALLOY

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
-	4.747	0.655	No Creep
-	9.495	1.331	No Creep
0	14.242	2.051	*
4650	"	"	
76650	"	"	
	"	"	
0	-	2.400	
72000	"	"	
0	18.9896	2.771	
4090	"	"	
68680	"	2.792	
0	23.737	3.447	
19720	"	3.469	
32600	"	"	
87240	"	3.490	
0	35.606	5.170	
3330	"	5.192	
12850	"	5.214	
24240	"	5.279	
0	47.474	6.937	
200	"	6.981	
30860	"	7.090	
83890	"	"	
0	59.343	8.988	
1750	"	9.097	
2600	"	"	
78360	"	9.381	

A.1 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi	SHEAR STRAIN $x10^{3}$	REMARKS
0	71.211	11.06	
100	"	12.369	
2010	"	13.722	
7400	"	14.616	
18600	"	15.511	
23960	"	15.772	
31480	"	16.012	
46140	"	16.427	
87220	"	17.147	
97610	"	17.256	
107460	"	17.408	
125160	"	17.671	
175000	"	18.107	
	59.343	16.427	
	47.474	14.682	
	35.606	13.002	
	23.737	11.257	
	14.242	9.795	
	4.747	8.377	
0	0	7.657	
6640	"	7.635	Creep recovery
16630	"	"	"
88030	"	7.613	"
after 22 hrs	"	7.613	

A.1 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi (Reverse)	SHEAR STRAIN $\times 10^{3}$	REMARKS
	-4.747	0.58*	No creep
8500	"	"	
0	-9.494	1.374	
13110	"	1.418	
28300	"	1.440	
90400	"	"	
0	-23.737	3.512	
9300	"	4.123	
75660	"	"	
0	-35.606	5.80	
980	"	6.283	
3950	"	6.414	
80010	"	6.654	
0	-47.474	8.399	
3300	"	9.250	
12120	"	9.446	
21600	"	9.468	
37200	"	9.555	
85190	"	9.577	
0	-59.343	11.191	
4290	"	12.980	
23870	"	13.198	
81270	"	13.438	

* All reverse load data referenced to new zero strain ($\epsilon_0 = 7.613 \times 10^{-3}$)

A.1 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi	SHEAR STRAIN $x10^{3}$	REMARKS
0	-71.211	15.096	
5800	"	16.667	
8720	"	17.038	
13340	"	17.670	
20490	"	17.997	
72270	"	19.001	
80910	"	19.110	
94590	"	19.328	
110560	"	19.437	
160040	"	19.874	
169850	"	20.004	
177300	"	20.026	
	-59.343	18.325	
	-47.474	16.536	
	-35.606	14.682	
	-23.737	12.915	
	-11.868	11.126	
	- 4.747	9.991	
0	0	9.250	

A.1 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi (2nd Forward Loading)	SHEAR STRAIN $x10^{3}$	REMARKS
0	4.747	0.720*	
7670	"	"	
65990	"	0.764	
0	9.495	1.440	
9900	"	1.593	
11730	"	1.636	
78600	"	1.658	
0	23.737	3.512	
7490	"	4.145	
16870	"	4.167	
25380	"	"	
87930	"	4.210	
0	35.606	5.803	
200	"	6.326	
8570	"	6.588	
21330	"	6.632	
63000	"	6.785	
0	47.474	8.202	
5880	"	9.490	
18680	"	9.577	
25900	"	9.620	
47290	"	9.664	
109490	"	9.839	
0	59.343	11.300	
1000	"	12.718	
82020	"	13.634	

*All 2nd forward load data referenced to new aero strain (ε_o=9.250x10^{-3})

A.1 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
0	71.211	15.205	
750	"	17.648	
17950	"	19.350	
69050	"	20.113	
79150	"	20.288	
93750	"	20.572	
141100	"	20.855	
151920	"	20.899	
163090	"	"	
167550	"	20.942	
	59.343	19.175	
	47.474	17.343	
	35.606	15.620	
	23.737	13.809	
	11.868	12.020	
	4.747	10.951	
0	0	10.166	
61200	"	10.079	Creep Recovery
151200	"	"	

A.1 Continued

INSTANTANEOUS SHEAR STRESS OF 71.211 KSI

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
0	71.211	10.755	
200	"	11.824	
1140	"	12.326	
3640	"	12.849	
12110	"	13.416	
74550	"	14.703	
82030	"	14.747	
92990	"	14.965	
101780	"	15.074	
333770	"	16.209	
	0	6.043	

A.2 $\alpha-\beta$ ANNEALED ALLOY

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi	SHEAR STRAIN $x10^{3}$	REMARKS
	4.747	0.676	No Creep
	9.945	1.33	No Creep
	14.242	2.116	No Creep
0	18.990	2.836	
13260	"	2.880	
24720	"	2.945	
78720	"	2.945	
0	21.363	3.250	
5300	"	3.272	
17030	"	3.294	
29618	"	"	
85838	"	"	
0	35.606	5.300	
6320	"	5.497	
20540	"	5.519	
57610	"	"	
0	47.474	7.024	
3120	"	7.264	
17970	"	7.330	
28210	"	7.352	
86710	"	7.374	
0	59.343	9.100	
11530	"	9.250	
19710	"	"	
23270	"	9.272	
108770	"	9.293	
0	71.211	11.191	
1740	"	12.631	
2940	"	13.045	
24240	"	17.081	

A.2 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi	SHEAR STRAIN $x10^{3}$	REMARKS
63500	71.211		
93450	"	26.505	
134780	"	29.363	
153300	"	30.563	
163530	"	31.152	
	59.343	29.385	
	47.474	27.574	
	35.606	25.785	
	23.737	23.866	
	14.242	22.382	
	4.745	20.790	
	0	19.961	

A.2 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ (Reverse) psi	SHEAR STRAIN $x10^{3}$	REMARKS
	-4.747	0.742*	No Creep
0	-9.495	1.549	
140	"	1.614	
61200	"	1.789	
	-23.737	4.014	
225	"	4.756	
7510	"	4.996	
13000	"	5.039	
27300	"	5.105	
48750	"	5.127	
91530	"	5.148	
0	-35.606	7.00	
1090	"	8.202	
2520	"	8.268	
11760	"	8.552	
39380	"	8.748	
82640	"	8.813	
0	-47.474	10.689	
7580	"	13.002	
13370	"	13.176	
85040	"	13.678	
0	-59.343	15.532	
1990	"	18.739	
5700	"	19.830	
20250	"	20.244	
87330	"	20.942	

* All reverse load data referenced to new zero strain (ϵ_o=19.361x10^{-3})

A.2 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ (Reverse) psi	SHEAR STRAIN $x10^{3}$	REMARKS
0	-71.211	22.797	
280	"	26.789	
3010	"	30.519	
10630	"	33.093	
15330	"	34.620	
32250	"	36.737	
85210	"	39.202	
114940	"	40.183	
120900	"	40.314	
159480	"	41.100	
176840	"	41.514	
184990	"	41.863	
	-59.343	40.052	
	-47.474	38.220	
	-35.606	36.387	
	-23.737	34.599	
	-11.868	32.635	
	-4.747	31.196	
	0	30.650	

A.2 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ (2nd Forward Loading) psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
0	4.747	0.655*	
900	"	0.698	
0	9.495	1.462	
3700	"	1.636	
60740	"	1.702	
0	23.737	3.600	
7380	"	4.232	
24150	"	4.625	
86660	"	4.712	
0	35.606	6.24	
4460	"	7.679	
10310	"	7.744	
22120	"	7.832	
34880	"	7.919	
85700	"	8.050	
0	47.474	9.293	
7929	"	11.911	
12790	"	11.998	
24850	"	12.173	
89650	"	12.478	
0	59.343	13.787	
1410	"	17.125	
5600	"	17.823	
263590	"	19.634	

* All 2nd forward load data referenced to new zero strain ($\epsilon_o = 30.650 \times 10^{-3}$)

A.2 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
0	71.211	21.291	
150	"	24.716	
2740	"	29.298	
6560	"	30.956	
10080	"	31.785	
60200	"	36.278	
87270	"	37.369	
146440	"	38.940	
155930	"	39.202	
163770	"	39.398	
172830	"	39.551	
232700	"	40.750	
242830	"	40.925	
255710	"	41.339	
309100	"	42.168	
333700	"	42.539	
	59.343	40.750	
	47.474	39.005	
	35.606	37.129	
	23.737	35.340	
	11.868	33.486	
	4.747	32.177	
	0	31.435	

A.3 RECRYSTALLIZATION ANNEALED ALLOY

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
-	4.7474	0.676	No Creep
-	9.4948	1.309	No Creep
-	14.2422	2.094	No Creep
0	18.9896	2.771	
19620	"	2.901	
59300	"	"	
0	23.7370	2.600	
6690	"	3.665	
27400	"	3.709	
85850	"	3.730	
	35.606	5.476	
4060	"	5.585	
8100	"	5.607	
19320	"	5.628	
83500	"	"	
	47.474	7.374	
320	"	7.461	
34730	"	7.613	
73180	"	7.635	
	59.343	9.468	
3500	"	9.708	
41280	"	9.926	
80000	"	9.991	
89160	"	10.013	
	71.211	11.955	
100	"	12.784	
2000	"	15.096	
5100		17.016	
8460	"	17.539	

A.3 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
13530	71.211	20.724	
18540	"	22.470	
20630	"	23.080	
3272	"	26.091	
37300	"	27.051	
77970	"	32.548	
87690	"	33.486	
109560	"	35.188	
112260	"	35.449	
164710	"	38.351	
183520	"	39.223	
189260	"	39.442	
	59.343	37.805	
	47.474	35.908	
	35.606	34.053	
	23.737	32.199	
	18.990	31.501	
	14.242	30.716	
	9.495	29.952	
	4.747	29.123	
	0	28.272	
After 24 hrs	"	28.185	Creep Recovery

A.3 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi (Reverse)	SHEAR STRAIN $\times 10^{3}$	REMARKS
-	-4.747	0.633*	No Creep
0	-9.495	1.418	
8500	"	1.549	
109800	"	1.658	
0	-23.737	3.512	
129600	"	5.083	
After 3 hrs	"	"	
0	-35.606	6.697	
3200	"	8.421	
61200	"	8.726	
0	-47.474	10.209	
4690	"	13.220	
7860	"	13.373	
8900	"	13.896	
58200	"	14.354	
	-59.343	16.099	
29400	"	22.928	
58520	"	23.735	
0	-71.211	25.502	
7430	"	38.896	
21670	"	41.645	
26620	"	42.299	
84820	"	46.052	
110020	"	47.055	

*All reverse load data referenced to new zero strain ($\varepsilon_o = 28.185 \times 10^{-3}$)

A.3 Continued

TIME SECONDS	SHEAR STRESS $\times 10^{-3}$ psi	SHEAR STRAIN $\times 10^{3}$	REMARKS
	-59.343	45.615	
	-47.474	41.739	
	-35.606	41.863	
	-23.737	39.965	
	- 9.495	37.762	
	- 4.747	36.824	
	0	36.060	
After 48 hrs	0	35.798	Creep Recovery
	2nd Forward		
	Loading		
	4.747	0.676*	No Creep
0	9.495	1.505	
5560	"	1.593	
17250	"	1.636	
55190	"	1.723	
0	23.737	4.101	
8740	"	4.756	
17240	"	4.799	
29080	"	4.821	
86840	"	4.952	
0	35.606	7.000	
9060	"	7.963	
16710	"	8.006	
77910	"	8.268	
0	47.474	10.100	
100	"	10.951	
7720	"	11.998	
16660	"	12.260	
24450	"	12.304	
100470	"	12.675	

*All 2nd forward load data referenced to new zero strain ($\epsilon_o = 35.798 \times 10^{-3}$)

A.3 Continued

TIME SECONDS	SHEAR STRESS $x10^{-3}$ psi	SHEAR STRAIN $x10^{3}$	REMARKS
0	59.343	14.507	
225	"	16.318	
3683	"	17.801	
84670	"	19.394	
0	71.211	21.401	
100	"	24.695	
200	"	25.524	
6720	"	31.610	
9930	"	32.286	
35710	"	35.362	
82510	"	37.260	
109510	"	38.351	
168460	"	39.834	
178460	"	40.052	
200860	"	40.511	
255460	"	41.774	
	64.090	40.183	
	59.343	39.442	
	47.474	37.587	
	35.606	35.668	
	23.737	33.835	
	9.495	31.501	
	4.747	30.650	
	0	29.887	
After 48 hrs	0	29.668	Creep Recovery

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13. ABSTRACT

Recent investigations have shown that Ti-6Aℓ-4V can exhibit an appreciable amount of creep at room temperature. In the present investigation three different microstructures (α*-β anneal, recrystallization anneal and β** anneal) of Ti-6Aℓ-4V were examined under dead weight torsional step loading. The loading sequence was forward, reverse and 2nd forward loading. It was concluded that even at a stress level well below the yield point the alloy exhibits creep in forward loading and increasing creep strain in reverse loading and 2nd loading. In addition the threshold stress for creep initiation is much lower in reverse loading and 2nd forward loading in comparison to forward loading. Furthermore the rate of creep at constant stress was different in different microstructures of the alloy; the maximum creep rate occurred with the recrystallization anneal and the minimum creep rate occurred with the β anneal. This type of creep would be important in design of structures subjected to long time cyclic loading.

* alpha-beta
** beta

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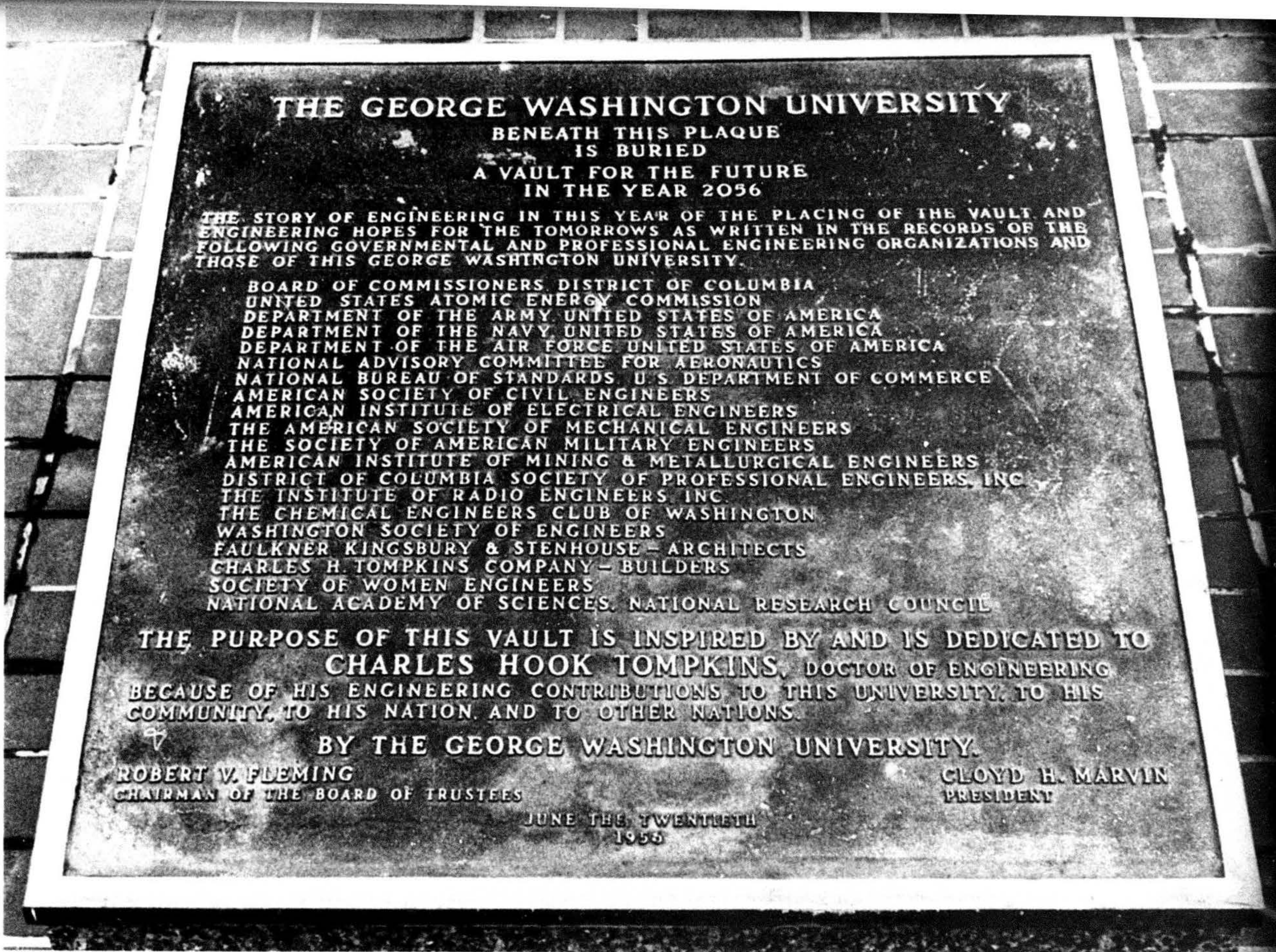
	ROLE	WT	ROLE	WT	ROLE	WT
Titanium alloys, Ti-6Aℓ-4V, room temperature, creep, 1st forward, 2nd forward, β anneal, recrystallization anneal, α-β anneal						



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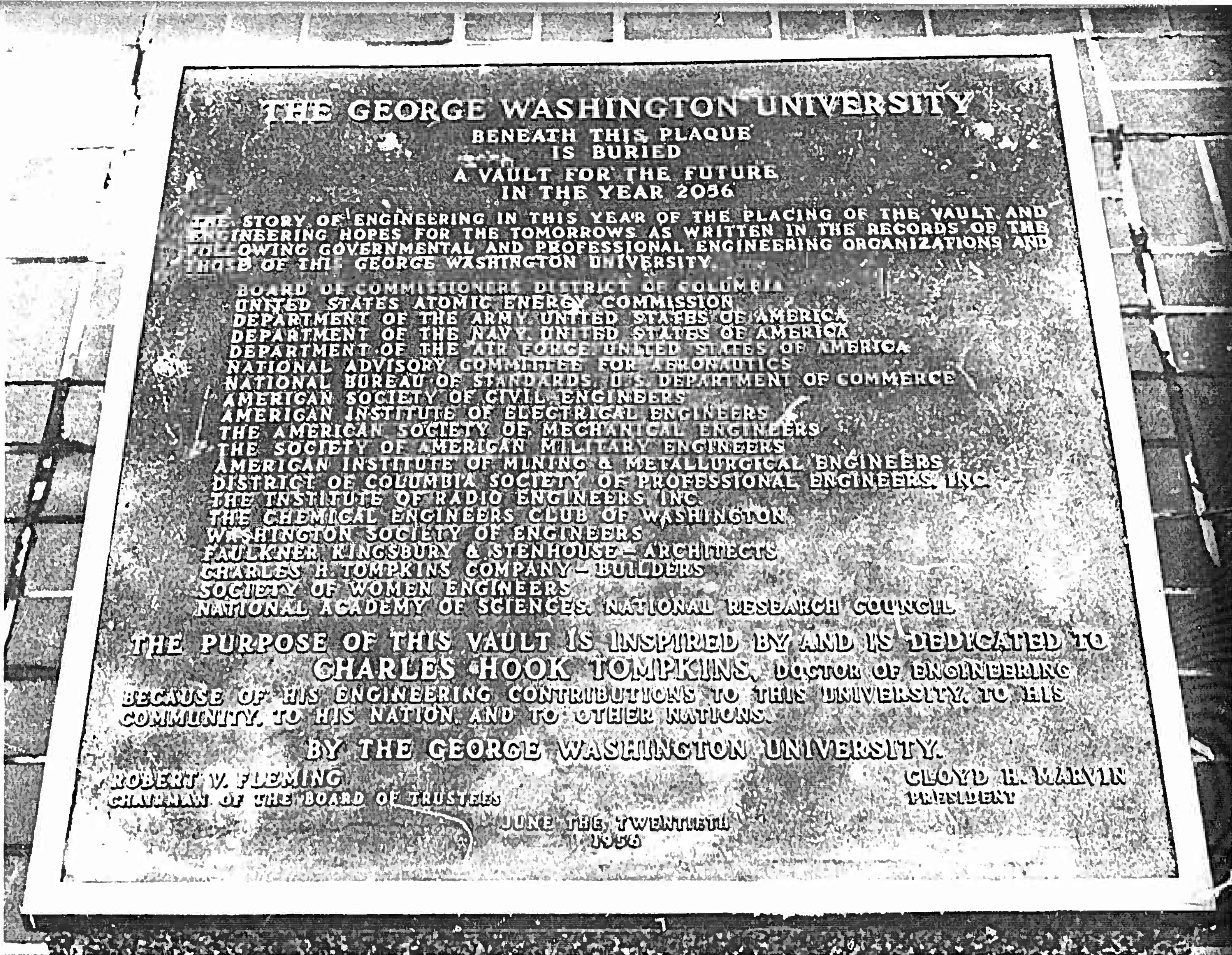

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